IMPRINT OF THE SUN ON THE SOLAR WIND

Richard Woo

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Shadia Rifai Habbal

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

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ABSTRACT

Observations of the inner corona in polarized brightness by the Mauna Loa Mk III K-coronameter and soft X-rays by Yohkoh of the inner corona are combined with Ulysses radio occultation measurements of the solar wind to demonstrate that the signature of active regions and bright points is present in the heliocentric distance range of 10–30 Ro. The existence of this signature at such distances can be readily accounted for by open field lines rooted within the complex magnetic structures of active regions and bright points. Hence, with the exception of the small volume of interplanetary space occupied by the heliospheric current sheet that evolves from coronal streamers within a few solar radii of the Sun, small-scale raylike structures carry the imprint of the different density structures of the solar disk approximately radially into the heliosphere.

1. INTRODUCTION

A deeper understanding of the relationship between the Sun and the solar wind is emerging as a result of recent progress with remote sensing measurements of the solar corona. Radio occultation and white-light measurements show that coronal streamers dominate the inner corona, but evolve into the heliospheric current sheet within a few solar radii of the Sun, occupying only a small volume of interplanetary space (Wang et al. 1997, Woo 1997). They also reveal that the polar coronal hole boundary does not diverge significantly as is commonly assumed (e.g., Zirker 1977), but instead extends radially into interplanetary space (Woo and Habbal 1997a, Woo et al. 1998). Raylike structures originating in both polar coronal holes and quiet regions permeate the corona at all latitudes (Woo 1996a, Woo and Habbal 1997a, Woo et al. 1998). Model calculations show that they arise naturally when the three-dimensional structure of the corona is filled with open field lines having different densities (Habbal et al. 1998), presumably a consequence of non-uniform local heating at the Sun.

The purpose of this paper is to use radio occultation, white-light, and soft X-ray measurements to demonstrate that the raylike structures in the solar wind carry the imprint of the Sun almost radially outward into interplanetary space, including signatures of active regions and bright points.

2. OBSERVATIONS

The Ulysses radio occultation measurements that probed the solar wind in 1995 (DOY 54–74, Feb 23–Mar 15) from the south pole to the equator over a heliocentric distance range of 20-30 Ro have been described by Pätzold et al. (1995). Woo and Habbal (1997a) compared these data with daily white-light images made by the Mk III Mauna Loa K-coronameter (Fisher et al. 1981) to show the presence of raylike structures and the radial extension of the polar coronal hole boundary in the near-Sun solar wind. Further evidence has since been obtained with the SOHO LASCO white-light measurements (Woo et al. 1998).

Here we conduct a more quantitative comparison between pB, soft X-rays and Ulysses ranging and Doppler scintillation measurements. Both pB and ranging are a measure of the path-integrated density, while Doppler scintillation is a measure of fluctuations in path-integrated density. However, because of the three polarization directions, pB has a slightly different weighting function than the ranging and Doppler scintillation measurements, favoring structures closer to the plane of the sky than ranging. On the other hand, the X-ray intensity is a function of temperature and density squared. Hence the X-rays are even more heavily weighted to structures in the plane of the sky than pB. In addition, the temperature structure will also influence the comparison

Shown in Figure 1a is the Yohkoh soft X-ray synoptic map for Carrington rotation 1892 produced by the X-ray measurements made at central meridian. The closest approach points of the Ulysses radio path covering DOY (day of year) 62–74 have been mapped to the Sun and superimposed on Figure 1a to show that the Ulysses radio occultation measurements probed the solar wind over an active region on the Sun. Reproduced from Woo and Habbal (1997) are the time series of Ulysses ranging measurements (in terms of total electron content characterized by hexems or 10^{16} electrons/m^2) in Figures 1b and 1c and of Doppler scintillation in Figure 1e, all normalized to 25 Ro. Logarithmic scales are used in the different measurements so that relative changes can be readily discerned and compared. The corresponding position angles of the closest approach points of the Ulysses radio path are shown at the top of Figure 1b (position angle is with respect to ecliptic north and increases counterclockwise).

A comparison of ranging with pB and soft X-ray is shown in Figures 1b and 1c, and pB with soft X-ray in Figure 1d. In addition, the Doppler Scintillation is plotted with the soft X-ray emission in Figure 1e. The closest distance to the solar disk that these measurements can be made is 1.15 Rs for pB, and 1.03 Rs for soft X-rays. The pB and soft X-ray measurements are obtained from daily images, and have a lower temporal resolution than the radio measurements. The traces of the coronal hole boundary, streamer stalk, active region and bright point on DOY 59, 67, 68, 72, respectively are indicated by the red (green for streamer stalk) dashed vertical lines. For further comparison, daily images in soft X-rays corresponding to these days (except for the streamer stalk on DOY 67) are given in Figures 1f–1h. The blue arrows drawn on these images indicate the corresponding directions of the closest approach points of the Ulysses radio path.

The first striking result to emerge from the comparison of the different data sets shown in Figure 1, is that the Ulysses ranging and Doppler scintillation measurements at 20-30 Ro both follow the general structure of the inner corona as observed in soft X-rays and in pB, below 1.15 Ro. The next remarkable result is the *radial* extension of distinct structures, namely the coronal hole boundary, the active region and the bright point from the inner corona, starting at 1.03 Ro to 30 Ro. This imprint at 30 Ro can only be transported by open field lines. Hence, taken together these data show very clearly how density structures on the solar disk project radially outwards into interplanetary space. Furthermore, the fact that there is a fairly good match in the path-integrated profiles between the Sun and 30 Ro in Figure 1b implies that the radial gradient of density does not vary significantly over the Sun.

Figure 1d shows that the relative enhancement in soft X-rays is significantly stronger than that of pB over the active region. Similar differences in relative change are observed in the comparison of azimuthal scans of daily soft X-ray and pB images. These daily scans show considerable structure over active regions which cannot readily be compared with that observed in ranging measurements. A meaningful comparison can only be made if the soft X-ray measurements are made with a high temporal cadence in order to match the high resolution of the ranging measurements in the longitudinal direction. Still, it is interesting to note that structure observed over active regions in soft X-rays can be observed to extend radially to altitudes of at least 1.35 Ro in the Mauna Loa pB images.

Doppler scintillation, like soft X-rays, shows a significantly stronger relative enhancement than ranging over active regions, and its profile looks remarkably similar to that of soft X-rays, as shown in Figure 1e. This striking result is not surprising since Doppler scintillation reflects the density variations (gradients) across the filamentary structures, and the strong enhancement in Doppler scintillation is consistent with the large temperature variations observed in loops forming active regions (e.g., Habbal et al. 1985, Arndt et al. 1994). Furthermore, since the physical characteristics of bright points are similar to those of active regions (Habbal 1992), it is not surprising that bright points are also be manifested in interplanetary space. The signature of the bright point on DOY 72 (May 13) is weak in ranging, but stronger in scintillation, just as it is for active regions.

Finally, streamer stalks observed in the the upper corona do not always overlie active regions (see e.g., Wang et al. 1997). In cases where they do, there is little chance for confusing streamer stalk and active region in Doppler scintillation measurements, because the signature of a streamer stalk is distinctly narrower (corresponding to an angular size of a few degrees) and more strongly enhanced than that of an active region, as shown in Figure 1e. An example of the detection of a streamer stalk in Doppler scintillation measurements in the absence of active regions is that by Galileo on 22 January 1997 (Habbal et al. 1997).

3. DISCUSSION AND CONCLUSIONS

The results of this letter sharpen our understanding of the relationship between the Sun and the solar wind, which can be summarized as follows. Bright large-scale coronal streamers dominate the corona at the Sun, giving the false impression of diverging polar coronal holes (Woo et al. 1998). Within a few solar radii, the streamers evolve into the heliospheric current sheet (Woo 1997), occupying only a small volume of interplanetary space (Wang et al. 1997), and carrying the slowest solar wind (Habbal et al. 1997). In the remaining vast regions of interplanetary space, a hierarchy of faint low-contrast raylike structures (Woo 1996, Woo and Habbal 1997a) follow open field lines and thread their way through closed field regions, as have been observed in high spatial resolution white-light images (November and Koutchmy 1996), to carry the imprint of the Sun approximately radially into interplanetary space. These raylike structures, rooted in small-scale features all over the Sun, span supergranular to kilometer scale sizes (Woo and Habbal 1997b).

In spite of evolution with heliocentric distance, there is evidence for the above picture in measurements of the solar wind beyond the 20–30 Ro region probed by the Ulysses radio occultation measurements. Radially aligned structures have been observed in the inner heliosphere by Helios in situ plasma measurements (Thieme et al.1989, 1990). When Yohkoh soft X-ray synoptic maps were correlated with IPS (interplanetary scintillation measurements that reflect density fluctuations) maps based on measurements by the Mullard Radio Astronomy Observatory in Cambridge, UK beyond 0.5 AU, a better match was found for the active regions than the heliospheric current sheet (Hick et al. 1995). The heliospheric current sheet is not detected by the Cambridge array, because the enhanced density fluctuations associated with the heliospheric current sheet span an angular size of only a few degrees (Woo et al. 1995, Habbal et al. 1997), too small to be observed by the Cambridge array. Although compressive fluctuations resulting from the dynamic interaction between slow and fast streams are present beyond 0.5 AU, as observed in IPS (Ananthakrishnan et al. 1980) and Doppler scintillation (Woo et al. 1995) measurements, the correlation found between IPS and Yohkoh measurements indicates that remnants of the imprint of the active region must also survive there.

The breakthrough in the recently evolved view of the origin and evolution of the solar wind resulted from the realization that low-frequency density fluctuations — long thought to represent convected inhomogeneities in phase/Doppler scintillation measurements (Woo and Armstrong 1979, Coles et al. 1991), and the least understood of solar wind fluctuations in terms of physical processes such as waves and turbulence (Bavassano 1994, Tu and Marsch 1995) — represent small-scale raylike structures (Woo 1996b). That the imprint of the Sun should extend into the solar wind is a consequence of these ubiquitous structures which provide the natural link between the Sun and the solar wind. That small-scale raylike structures should play a major role in the steady state solar wind is not surprising in light of the generally filamentary nature of the photospheric fields (Almeida 1997). Recent photospheric magnetic field observations have shown that individual elements come and go on very short time scales, with the flux on the surface, outside of active regions, being completely replaced every few days (Title 1997). As in the density structures associated with the steady solar wind, there are differences between the small- and large-scale magnetic field, with the large-scale field exhibiting a solar cycle dependence, but the small-scale none (Harvey 1992, Hoeksema 1997). The seemingly independent roles of small- and large-scale magnetic structures in the steady solar wind is also reminiscent of similar differences noted in the relationship of coronal mass ejections to small-scale structures such as sunspots, active regions or Hα flares, as opposed to large-scale magnetic structures such as streamers and prominences (Hundhausen 1992). It is clear that small-scale structures are a fundamental component of the solar wind, and that an understanding of coronal heating and acceleration of the solar wind cannnot be achieved without first understanding the role of the small-scale structures (Habbal 1992).

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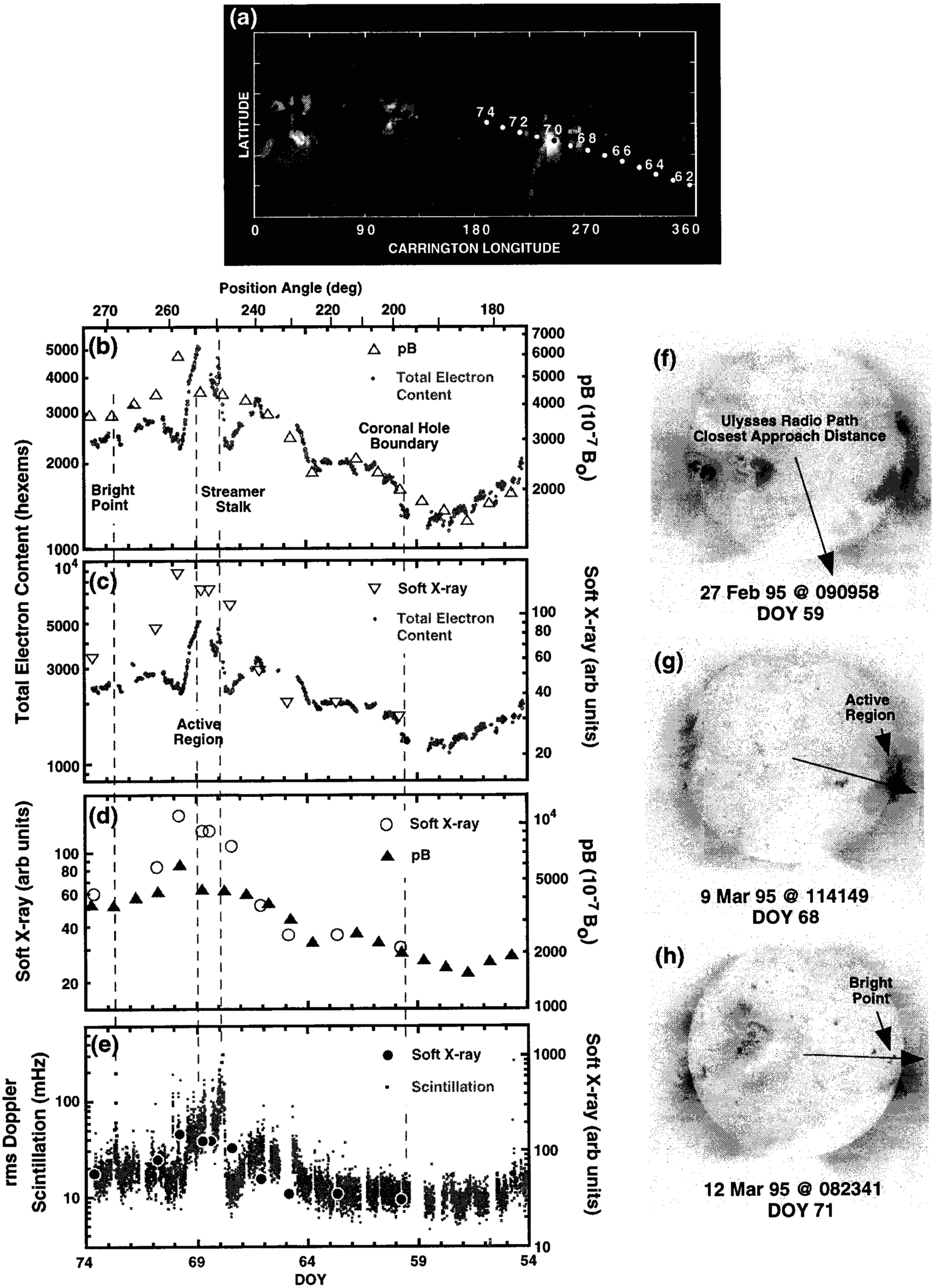
FIGURE CAPTIONS

Figure 1 (a) Ulysses radio occultation measurements took place during the period DOY (day of year) 54–62 (23 Feb 1995 –15 Mar 1995). The closest approach points of the Ulysses radio path have been mapped back to the Sun and superimposed on the synoptic map of Yohkoh soft X-rays for Carrington rotation 1892. The measurements of DOY 54-62 occurred in the southern polar coronal hole during Carrington rotation 1891 and are not shown. (b) Time series of ranging (in terms of total electron content characterized by hexems or 10^{16} electrons/m^2) (in blue) and Mauna Loa Mk III pB at 1.15 Ro (in red). Position angle of the radio measurements is indicated at the top of the figure. The red dashed vertical lines indicate the coronal hole boundary, active region, and bright point, while the green dashed vertical line indicates the evolved streamer stalk. (c) Same as (b) but ranging (blue) and Yohkoh soft X-ray at 1.03 Ro (red). (d) Time series of Yohkoh soft X-ray at 1.03 Ro (red) and Mauna Loa Mk III pB at 1.15 Ro (green). (e) Time series of Doppler scintillation (blue) and soft X-ray (red). (f)–(h) Daily Yohkoh soft X-ray images showing the solar features of: (f) coronal hole boundary, (g) active region and (h) bright point, indicated by red vertical lines in Figures 1(b)–(e). The blue arrows in (f)–(h) point to the directions of the closest approach points of the Ulysses radio occultation measurements.



(a)
LATITUDE
CARRINGTON LONGITUDE
0
90
180
270
360
74
72
70
68
66
64
62
Position Angle (deg)
270
260
240
220
200
180
(b)
pB
Total Electron Content
Bright Point
Streamer Stalk
Coronal Hole Boundary
pB (10^{-7} B_0)
Total Electron Content (hexems)
(c)
Soft X-ray
Total Electron Content
Active Region
Soft X-ray (arb units)
(d)
Soft X-ray
pB
Soft X-ray (arb units)
pB (10^{-7} B_0)
(e)
Soft X-ray
Scintillation
rms Doppler Scintillation (mHz)
Soft X-ray (arb units)
74
69
64
59
54
DOY
(f)
Ulysses Radio Path Closest Approach Distance
27 Feb 95 @ 090958
DOY 59
(g)
Active Region
9 Mar 95 @ 114149
DOY 68
(h)
Bright Point
12 Mar 95 @ 082341
DOY 71